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# Joint Downlink/Uplink Design for Wireless Powered Networks with Interference

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***Abstract*—This paper jointly investigates the downlink/uplink of wireless powered networks (WPNs), which are exposed to the effect of the *cascaded near-far problem*, i.e., the asymmetric overall degradation of the users' performance, due to different path-loss values. More specifically, assuming that the users are able to harvest energy both from interference and desired signals, higher path-loss reduces the downlink rate of the far user, while it also negatively affects its uplink rate, since less energy can be harvested during downlink. Furthermore, if the far user is located at the cell-edge, its performance is more severely impaired by interference, despite the potential gain due to energy harvesting from interference signals. To this end, we fairly maximize the downlink/uplink users' rates, by utilizing corresponding priority weights. Two communication protocols are taken into account for the downlink, namely time division multiple access (TDMA) and non orthogonal multiple access (NOMA), while NOMA with time-sharing is considered for the uplink. The formulated multidimensional non-convex optimization problems are transformed into the equivalent convex ones and can be solved with low complexity. Simulations results illustrate that: i) a relatively high downlink rate can be achieved, while the required energy is simultaneously harvested by the users for the uplink, ii) dowlink NOMA is a more appropriate option with respect to the network topology, especially when a high downlink rate is desired.**

***Index Terms*—energy harvesting, wireless powered networks, SWIPT, NOMA, resource allocation, interference**

## I. Introduction

THE opportunities arising from the recent adnavces in multimedia, along with the emerging future internet-of-things (IoT) applications, such as smart cities, health monitoring devices, and driverless cars, are limited by the finite battery capacity of the involved wireless communication devices [1], [2]. In this context, energy harvesting (EH), which refers to harnessing energy from the environment or other energy sources and converting to electrical energy, is regarded as a disruptive technological paradigm to prolong the lifetime of energy-constrained wireless networks. Apart from offering a promising solution for energy-sustainability of wireless nodes in communication networks [3], EH also reduces the operational expenses [1]. However, the main disadvantage of traditional energy harvesting methods is that they rely on natural resources, such as solar and wind energy, which are uncontrollable.

For this reason, harvesting energy from radio frequency signals, which also transfer information, seems to be an interesting alternative. This technique, referred to as *simultaneous wireless information and power transfer (SWIPT)*, presupposes the efficient design of the communication system that receives information and energy simultaneously [4], [5], which also depends on the specific system implementation [6], [7]. In this framework, the nodes use the power of the received signal to charge their batteries [8], or to transmit the information to the base station (BS) [9], [10]. However, in practice, nodes cannot harvest energy and receive/transmit information simultaneously [9], [11]–[14]. In order to overcome this problem, two strategies have been proposed, i.e., *power-splitting*, which is based on the division of the signal's power into two streams, and *time-splitting*, according to which, during a portion of time, the received signal is used solely for energy harvesting, instead of decoding [13], [15], [16]. The idea of SWIPT has been reported in various scenarios, such as one source-destination pair [8], multiple-input multiple-output (MIMO) communications systems [17]–[21], orthogonal frequency division multiple access (OFDMA) [8], [22]–[24], cooperative networks [25]–[32], communication systems with security [33]–[35], and cognitive radio [36], [37].

### A. Literature and Motivation

The joint design of downlink energy transfer and uplink information tranmission in multiuser communications systems has been initially investigated in [9]. By considering the time-splitting technique, the authors in [9] have proposed a novel protocol referred to as *harvest-then-transmit*, where the users first harvest energy, and then they transmit their independent messages to the BS, by using the harvested energy, while assuming time-division miltiple access (TDMA) for the uplink. Moreover, it has been shown that the rate and fairness can be substantially improved, when uplink non-orthogonal multiple access with time-sharing (NOMA-TS) is utilized [6], [38], [39]. A similar NOMA-based scenario has been investigated in [40] and [41], considering a multiantenna BS and massive MIMO, respectively. Note that NOMA, which has been recognized as a promising multiple access technique for fifth generation (5G) networks, is fundamentally different from TDMA, since its basic principle is that the users can achieve multiple

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access by using the power domain [42]–[45], implementing a joint processing technique, such as successive interference cancellation (SIC). Moreover, NOMA-TS is a generalization of uplink NOMA with fixed decoding order, so that a user, whose message suffers from strong interference for a specific decoding order, can experience a better reception reliability for another decoding order, during the implementation of SIC [46]–[49].

Downlink NOMA with SWIPT has been proposed in [50], which provides closed-form expressions for the outage probability of the users, assuming a cooperative communication system with multiple wireless powered relays. Moreover, in [51] the outage performance of cooperative relaying for two-user downlink NOMA systems is investigated, while a best near best far user selection scheme is proposed. Also, SIC in the downlink with SWIPT has been investigated in [52], which focuses on the coverage probability of a random user in bipolar ad hoc networks. It should be highlighted that the concept of downlink is different from that of the uplink NOMA, since in the downlink all users receive the interfering messages from the same source, i.e., via the same link [53]–[55]. For example, TS is a technique that cannot be applied in downlink NOMA. Interestingly, it has not be shown yet if and under which circumstances NOMA outperforms orthogonal schemes, e.g. TDMA, when used for the downlink of wireless powered networks (WPNs). Regarding this issue, it should also be considered that the utilization of downlink NOMA, in contrast to uplink NOMA, implies that SIC takes place at the energy harvesting users, and, thus, the corresponding complexity is increased.

On the other hand, the joint optimization of downlink and uplink information transmission in WPNs has been studied in [23], when the aim is to maximize the energy efficiency, while utilizing OFDMA. Interestingly, a user far from the BS of a WPN receives less power than a nearer user, therefore its uplink rate is negatively affected. A cascade effect of this phenomenon appears when information is also transmitted during the energy harvesting phase, using SWIPT, since the downlink rate of the far user is also affected. Moreover, the distance of a user from the BS also affects the level of the received interference, since, usually, users near the BS receive less interference compared to the cell-edge users, the performance of which is more severely impaired, despite the potential gain due to energy harvesting from interference signals. This effect, which we will hereafter call *cascaded near-far problem (CnfP)*, has not been investigated in the existing literature.

### B. Contribution

In this work, a WPN is considered in the presence of interference. The communication is performed in two phases; during the first phase, the BS transmits information to the users, while the users also harvest energy, and during the second phase, the users utilize the harvested energy in order to transmit their messages towards the BS. In this network setup, the CnfP is caused by: i) the difference in achievable user rates during downlink, due to their asymmetric positioning, ii) the difference in achievable user rates during uplink, due to different harvested energy during downlink, iii) the asymmetric impact of interference on the users, both for the information reception and the energy harvesting.

The presented analysis focuses on the optimal system design, in order to reduce the impact of CnfP in WPNs with interference, considering a sole communication channel and nodes with single antennas. More specifically, the following aspects are considered and optimized:

- Two well-known multiple access schemes are considered for the downlink, i.e., NOMA and TDMA, in order to investigate their performance in WPNs with interference. For the uplink, we assume NOMA-TS, based on the results of [38].
- We jointly maximize the minimum downlink and uplink rate, while achieving a balance between them, by adding a desirable weight for each rate in the optimization formulation. It is shown that the resulting high dimensional non-convex optimization problems can be transformed to convex ones and, thus, be optimally solved by well-known methods with low complexity.
- Based on the above optimization solutions, we investigate the CnfP and its impact on the performance of WPNs, for both communication protocols. The implementation of NOMA in the downlink is proved to offer gain over the TDMA protocol, especially in the case that the users are located at different distances from the BS, i.e., in the case that the CnfP is strong.
- Extensive comparison between the two considered protocols for the downlink also verifies that NOMA is a more energy efficient solution than TDMA for usage in the downlink of WPNs, both in the presence or the absence of interfering sources.

### C. Structure

The rest of the paper is organized as follows. Section II describes the energy harvesting and communication models, as well as the corresponding rates. In section III, the minimum rate among users, both in the downlink and in the uplink, is maximized considering priority gains for the downlink/uplink. In Section IV, simulation results are presented and discussed. Finally, Section V concludes the paper.

## II. System model

We consider both the downlink and the uplink of a wireless network consisting of $N$ users, denoted by $U_n$, with $n \in \mathcal{N} = \{1, ..., N\}$ and one BS. It is assumed that all users share the same bandwidth resources and all nodes are equipped with a single antenna. Assuming channel reciprocity, the channel between the BS and $U_n$, and the corresponding reciprocal, are denoted by $h_n$ and $\bar{h}_n$, respectively, where $\bar{(\cdot)}$ denotes the conjugate of $(\cdot)$, while the channel power gain is $g_n = |h_n|^2 = |\bar{h}_n|^2$. We further assume that all nodes consume energy only for information transmission. Moreover, an interfering source (IS) is assumed. In line with Fig. 1, where the considered system model is presented, the communication is divided into time frames of unitary duration, each of which consists of two distinct phases:

Phase 1 (downlink with SWIPT): The BS transmits power, denoted by $P$, which is used by the users in order to decode the BS's messages, as well as to charge their batteries. The duration of this phase is denoted by $0 \leq \tau \leq 1$. Two different protocols are considered, namely NOMA and TDMA.

Phase 2 (uplink): The remaining amount of time, i.e., $1-\tau$ is assigned to the users, in order to transmit their messages. We consider that NOMA-TS is used, since it was proven in [38] that it maximizes the rates and fairness among users.

### A. Downlink with NOMA

In this section, we describe the downlink phase, when downlink NOMA and simultaneous power transfer towards the users is applied. NOMA allows the BS to simultaneously serve all users by using the entire bandwidth to transmit data, through a superposition coding technique at the transmitter side. According to the NOMA protocol, the BS transmits the sum of the users' messages with the corresponding power, that is, $\sum_{n=1}^{N} \sqrt{P_n^d} s_n^d$, where $P_n^d$ and $s_n^d$, with $||s_n^d||^2 = 1$, are the allocated power and the message for the $n$-th user, respectively, while the superscript $(\cdot)^d$ denotes a value for the downlink phase. Moreover, the transmitting power is subject to

$$\sum_{n=1}^{N} P_n^d \leq P. \tag{1}$$

We assume that the signal received by each user, $U_n$, is split into two streams, and the power fraction, $0 \leq \theta_n \leq 1$, is used for information processing, while the fraction $1-\theta_n$ is devoted to energy harvesting. The observation at the $n$-th user which is used for information decoding is given by

$$y_n = h_n \sqrt{\theta_n} \sum_{i=1}^{N} \sqrt{P_i^d} s_i^d + \sqrt{\theta_n} I_n + \nu_n, \tag{2}$$

where $\nu_n$ denotes the additive noise at $U_n$ and $I_n$ is the interfering signal. In fact, noise is added in two parts of the receiver, i.e. the receive antenna noise and the circuit noise [15], [19]. However, the power of the antenna noise is too small and can be neglected, in line with [9], [50]. Thus, in (2), we include only one additive noise parameter.

Each user, $U_j$, carries out SIC, by detecting and removing the $U_n$'s message, for all $n < j$, from its observation [44], [54]. Thus, the achievable rate at $U_n$, $n \in \{1, 2, \cdots, N\}$, is bounded by

$$R_n^d = \min(R_{n\to n}^d, R_{n\to n+1}^d, ..., R_{n\to N}^d) \tag{3}$$

where $R_{n\to j}^d$ denotes the rate at which user $U_j$ detects the message intended for user $U_n$. In the above,

$$R_{n\to j}^d = \tau \log_2\left(1 + \frac{p_n^d \theta_j g_j}{\theta_j g_j \sum_{i=n+1}^{N} p_i^d + \theta_j p_{I,j} + 1}\right), \tag{4}$$

where $p_n^d = \frac{P_n^d}{N_0}$ and $p_{I,j} = \frac{P_{I,j}}{N_0}$, in which $P_{I,j}$ is the power of the received interference by $U_j$. We assume that $P_{I,j}$ is perfectly sensed by $U_j$ and reported to the BS in order to properly allocate the available resources. Note than when $n = N$, (4) is written as

$$R_{N\to N}^d = \log_2\left(1 + \frac{p_N^d \theta_N g_N}{\theta_N p_{I,N} + 1}\right). \tag{5}$$

Hereafter, $\boldsymbol{p} = \{p_1^d, \ldots, p_N^d\}$ denotes the set of values of transmit power among users and, $\boldsymbol{\theta} = \{\theta_1, \ldots, \theta_N\}$, the set of power splitting factors among users.

The harvested energy by each user is given by

$$E_n = \eta\tau(1-\theta_n)\left(g_n \sum_{i=1}^{N} P_i + P_{I,n}\right), \tag{6}$$

where $0 < \eta < 1$ is the efficiency of the energy harvester.

*1) Special Case: Interference-free Downlink:* In the case of absence of interfering sources and without loss of generality, the values $\theta_n g_n$ enforced to be sorted according to the users' ordering, i.e.,

$$\theta_1 g_1 \leq \theta_2 g_2 \leq \cdots \leq \theta_N g_N. \tag{7}$$

Thus, the achievable data rate at $U_n$, $n \in \{1, 2, \cdots, N\}$, can be obtained as

$$R_n^d = \tau \log_2\left(1 + \frac{p_n^d \theta_n g_n}{\theta_n g_n \sum_{i=n+1}^{N} p_i^d + 1}\right), \tag{8}$$

which for $n = N$ is written as

$$R_N^d = \tau \log_2\left(1 + p_N^d \theta_N g_N\right). \tag{9}$$

Note that (8) is conditioned on $R_{n\to j}^d \geq \bar{R}_n^d$, $\forall n < j$, where $\bar{R}_n^d$ denotes the targeted rate of $U_n$. When $\bar{R}_n^d$ is determined opportunistically through the user's channel condition, i.e., $\bar{R}_n^d \leq R_n^d$, it can be easily verified that the condition $R_{n\to j}^d \geq \bar{R}_n^d$ always holds since $\theta_j g_j \geq \theta_n g_n$ for $j > n$. Consequently, the users' data rates can be given directly by (8).

### B. Downlink with TDMA

When TDMA is used in the downlink, the BS serves by sequentially sending the non-interfering signals, $s_n^d, n \in \mathcal{N}$, with transmit power $P$. In this case,

$$\sum_{n=1}^{N} t_n \leq \tau, \tag{10}$$

where $t_n \geq 0$ denotes the amount of time that is allocated to each user. Hereinafter, $\boldsymbol{t} = \{t_1, \ldots, t_N\}$, will be used to denote the set of values of allocated time among users.

Thus, during the time allocated for the $m$-th user, $U_n$ receives

$$y_n = h_n \sqrt{P} s_m^d + I_n + \nu_n, \quad m \neq n. \tag{11}$$

We assume that when the BS transmits the message of the $m$-th user, the $n$-th user utilizes all the received power for harvesting. On the other hand, when $m = n$, its own message is transmitted by the BS. Then, we assume that $U_n$ splits the received power in two streams, i.e., the power fraction $\theta_n$ is used for information processing, while the fraction $1-\theta_n$ is

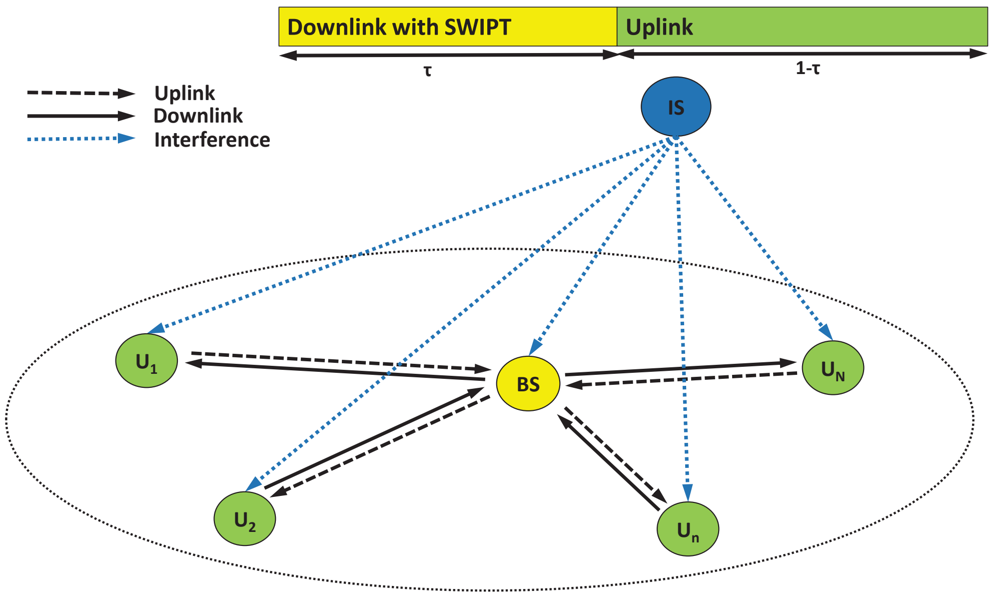


Fig. 1. Sequential downlink (with simultaneous energy transfer) and uplink in wireless powered networks with multiple users and interference.

used for harvesting. In that case, the received signal is given by

$$y_n = h_n\sqrt{\theta_n P}s_n^d + \sqrt{\theta_n}I_n + \nu_n, \tag{12}$$

and the corresponding rate is

$$R_n^d = t_n \log_2(1 + \frac{\theta_n p g_n}{\theta_n p_{I,n} + 1}), \tag{13}$$

with $p = \frac{P}{N_0}$. Finally, the total harvested energy is given by

$$E_n = \eta(g_n P + P_{I,n}) \sum_{i\in\mathcal{N}} t_i - \eta\theta_n t_n (g_n P + P_{I,n}). \tag{14}$$

## C. Uplink

It is highlighted that Phase 2, i.e., the uplink phase, is common for both methods assumed for the downlink. TS can be combined with NOMA for the uplink, since the decoding of all messages takes place at the BS, in contrast to downlink NOMA. Therefore, NOMA-TS has been selected for the uplink, according to which all users simultaneously send their messages, $s_n^u$, where $||s_n^u||^2 = 1$, with transmit power $P_n^u$ for the $n$-th user, while the superscript $(\cdot)^u$ denotes a value for the uplink phase. Thus, the observation at the BS is given by

$$y = \sum_{n=1}^{N} \bar{h}_n \sqrt{P_n^u} s_n^u + I + \nu, \tag{15}$$

where $I$ denotes the interfering signal and $\nu$ denotes the additive noise at the BS. By using SIC and TS, the capacity region is bounded by [38]

$$\sum_{n\in\mathcal{M}_k} R_n^u \leq (1-\tau)\log_2\left(1 + \frac{\sum_{n\in\mathcal{M}_k} p_n^u g_n}{p_I + 1}\right), \quad \forall\mathcal{M}_k : \mathcal{M}_k \subseteq \mathcal{N} \tag{16}$$

with $R_n^u$ being the uplink rate achieved by the $n$-th user, $p_n^u = \frac{P_n^u}{N_0}$, $p_I = \frac{P_I}{N_0}$, $N_0$ is the noise power, and $P_I$ is the power of the interference received by the BS. We assume that $P_I$ is perfectly sensed by the BS. Finally, $\mathcal{M}_k$ denotes any possible subset of the users.

It is assumed that the energy required to receive/process information is negligible compared to the energy required for information transmission [37], [50], [56]. Thus, when users utilize solely the energy that they harvest during the 1-st phase, denoted by $E_n$, to transmit their information, then $P_n^u$ can be calculated as

$$P_n^u = \frac{E_n}{1-\tau}. \tag{17}$$

Note that the harvested energy, $E_n$, depends on the selected protocol for the downlink, i.e. NOMA or TDMA.

# III. Resources Allocation Optimization

In this section, we seek to maximize both the downlink and the uplink rate, while achieving: i) fairness among users, by ensuring that the maximized rate can be achieved by each of them, and ii) a balance between the downlink and the uplink rate. To this end, an auxiliary variable $\mathcal{R}$ is used, which denotes the lower bound of the weighted downlink/uplink rates, i.e. $\frac{R_n^d}{\alpha}$ and $\frac{R_n^u}{\beta}$, where $\alpha, \beta \geq 0$, with $\alpha + \beta = 1$, correspond to the weights used for the downlink and uplink, respectively. Thus, according to the above, it must hold that

$$R_n^d \geq \alpha\mathcal{R}, \tag{18}$$

and

$$R_n^u \geq \beta\mathcal{R}, \tag{19}$$

For example, when $\alpha = 1$ or $\alpha = 0$, only the downlink or uplink is optimized, respectively. By setting $\alpha = 0.5$, we aim to achieve the same rate for both the downlink and the uplink. Moreover, in the problem formulation, regarding the downlink, we take into account the specific formulation according to both protocols that are presented in Section II.

### A. Downlink with NOMA

Taking into account (17) and (6), the constraint in (16) can be rewritten as

$$\sum_{n\in\mathcal{M}_k} R_n^u \leq (1-\tau)\log_2\left(1+\frac{\eta\tau\sum\limits_{n\in\mathcal{M}_k}(1-\theta_n)g_n\left(g_n\sum\limits_{i=1}^{N}p_i^d+p_{I,n}\right)}{(1-\tau)(p_I+1)}\right), \forall\mathcal{M}_k:\mathcal{M}_k\subseteq\mathcal{N}. \quad (20)$$

The minimum rate maximization problem can be written as

$$\begin{aligned}\max_{\mathcal{R},\tau,\boldsymbol{p},\boldsymbol{\theta}} \quad & \mathcal{R}\\ \textbf{s.t.} \quad & \mathrm{C}_1: \min(R^d_{n\to n}, R^d_{n\to n+1},...,R^d_{n\to N})\geq \alpha\mathcal{R}, \forall n\in\mathcal{N}\\ & \mathrm{C}_2: (1-\tau)\log_2\left(1+\frac{\eta\tau\sum\limits_{n\in\mathcal{M}_k}(1-\theta_n)g_n\left(g_n\sum\limits_{i=1}^{N}p_i^d+p_{I,n}\right)}{(1-\tau)(p_I+1)}\right)\\ & \qquad \geq \beta|\mathcal{M}_k|\mathcal{R},\ \forall\mathcal{M}_k\subseteq\mathcal{N},\\ & \mathrm{C}_3: \textstyle\sum_{n=1}^N p_n^d\leq p,\\ & \mathrm{C}_4: 0\leq\theta_n\leq 1,\ \forall n\in\mathcal{N},\\ & \mathrm{C}_5: p_n^d\geq 0,\ \forall n\in\mathcal{N},\\ & \mathrm{C}_6: 0\leq\tau\leq 1,\end{aligned} \quad (21)$$

where $|.|$ denotes cardinality and $\mathrm{C}_1$, $\mathrm{C}_2$, $\mathrm{C}_3$ correspond to (3) and (18), (19) and (20), and (1), respectively, while the remaining constraints (i.e., $\mathrm{C}_4$-$\mathrm{C}_6$) force the optimized variables not to exceed their maximum/minimum value.

Using the epigraph form of (21), it can be rewritten as

$$\begin{aligned}\max_{\mathcal{R},\tau,\boldsymbol{p},\boldsymbol{\theta}} \quad & \mathcal{R}\\ \textbf{s.t.} \quad & \mathrm{C}_1: \tau\log_2\left(1+\frac{p_n^d\theta_j g_j}{\theta_j g_j\sum_{i=n+1}^N p_i^d+\theta_j p_{I,j}+1}\right)\geq\alpha\mathcal{R},\\ & \qquad \forall n\in\mathcal{N}, j\in\{n,...,N\},\\ & \mathrm{C}_2: (1-\tau)\log_2\left(1+\frac{\eta\tau\sum\limits_{n\in\mathcal{M}_k}(1-\theta_n)g_n\left(g_n\sum\limits_{i=1}^{N}p_i^d+p_{I,n}\right)}{(1-\tau)(p_I+1)}\right)\\ & \qquad \geq \beta|\mathcal{M}_k|\mathcal{R},\ \forall\mathcal{M}_k\subseteq\mathcal{N},\\ & \mathrm{C}_3: \textstyle\sum_{n=1}^N p_n^d\leq p,\\ & \mathrm{C}_4: 0\leq\theta_n\leq 1,\ \forall n\in\mathcal{N},\\ & \mathrm{C}_5: p_n^d\geq 0,\ \forall n\in\mathcal{N},\\ & \mathrm{C}_6: 0\leq\tau\leq 1.\end{aligned} \quad (22)$$

Note that the epigraph form is a useful tool from optimization theory. It represents a set of points (i.e., a graph) above or below the considered function [57].

*Proposition 1:* The inequality in $\mathrm{C}_3$ can be replaced by equality, without excluding the optimal from the set of all solutions.

*Proof:* Let's assume that the optimal $\mathcal{R}$, denoted by $\mathcal{R}^*$ is achieved when $\boldsymbol{p}^*=\{p_1^*,...,p_N^*\}$, for which $\sum_{n=1}^N p_n^*<p$. Let $\boldsymbol{p}'$ be another power vector, for which $\boldsymbol{p}'=\{p-\sum_{n=2}^N p_n^*, p_2^*,...,p_N^*\}$, i.e., it is the same vector as $\boldsymbol{p}^*$, apart from the power allocated to the first user. Since $\sum_{n=1}^N p_n'=p$, it is $p_1'>p_1^*$ and thus the rates at which all users (including $U_1$) detect the message of the $U_1$ is improved. Thus, since $R_1^d=\min(R^d_{1\to 1},R^d_{1\to 2},...,R^d_{1\to N})$, $R_1^d$ is increased. At the same time, the values for the rest users' rates are retained, since the message of the first user is canceled by the rest of the users. Therefore, all users' rates remain the same, while $R_1^d$ is increased. In this way, all inequalities regarding $\mathcal{R}^*$ are still satisfied. Thus, at least $\mathcal{R}^*$ can be achieved by $\boldsymbol{p}'$, contradicting the sole optimality of $\boldsymbol{p}^*$. ■

Proposition 1 is critical for the replacement of the constraint in $\mathrm{C}_2$ with

$$(1-\tau)\log_2\left(1+\frac{\eta\tau\sum\limits_{n\in\mathcal{M}_k}(1-\theta_n)g_n\left(g_n p+p_{I,n}\right)}{(1-\tau)(p_I+1)}\right) \geq \beta|\mathcal{M}_k|\mathcal{R},\ \forall\mathcal{M}_k\subseteq\mathcal{N}. \quad (23)$$

The time splitting parameter, $\tau$, which appears in the capacity formula in both the downlink and uplink, couples the power allocation variables $\boldsymbol{p}$ and $\boldsymbol{\theta}$ and results in a non-convex problem. We note that there is no standard approach for solving non-convex optimization problems in general.

In order to overcome this issue and provide a tractable solution, we perform a full search with respect to $\tau$. Particularly, for a given value of $\tau$, we optimize the variables $\boldsymbol{p}$ and $\boldsymbol{\theta}$ with the aim to maximize the corresponding minimum rate. We repeat the procedure for all possible values of $\tau$ and record the corresponding achieved values of $\mathcal{R}$.

However, even with this simplification the problem remains non-convex, with respect to $\boldsymbol{p}$ and $\boldsymbol{\theta}$, which are coupled. To this end, we set $p_n^d\triangleq\exp(\tilde{p}_n)$, $\theta_n\triangleq\exp(\tilde{\theta}_n)$, and $\mathcal{R}\triangleq\exp(\tilde{\mathcal{R}})$, and the optimization problem in (22), after some mathematic manipulations, can now be written as

$$\begin{aligned}\max_{\tilde{\mathcal{R}},\tilde{\boldsymbol{p}},\tilde{\boldsymbol{\theta}}} \quad & \tilde{\mathcal{R}}\\ \textbf{s.t.} \quad & \mathrm{C}_1: \tau\log_2\left(1+\frac{\exp(\tilde{p}_n)\exp(\tilde{\theta}_j)g_j}{\exp(\tilde{\theta}_j)g_j\sum_{i=n+1}^N\exp(\tilde{p}_i)+\exp(\tilde{\theta}_j)p_{I,j}+1}\right)\\ & \qquad \alpha\geq\exp(\tilde{\mathcal{R}}),\ \forall n\in\mathcal{N}, j\in\{n,...,N\},\\ & \mathrm{C}_2: (1-\tau)\log_2\left(1+\frac{\eta\tau\sum\limits_{n\in\mathcal{M}_k}\left(1-\exp(\tilde{\theta}_n)\right)g_n(g_n p+p_{I,n})}{(1-\tau)(p_I+1)}\right)\\ & \qquad \geq\beta|\mathcal{M}_k|\exp(\tilde{\mathcal{R}}),\ \forall\mathcal{M}_k\subseteq\mathcal{N}\\ , \quad & \mathrm{C}_3: \textstyle\sum_{n=1}^N\exp(\tilde{p}_n)=p,\\ & \mathrm{C}_4: 0\leq\exp(\tilde{\theta}_n)\leq 1,\\ & \mathrm{C}_5: \exp(\tilde{p}_n)\geq 0,\end{aligned} \quad (24)$$

which is still non-convex. However, after some mathematic manipulations and by relaxing the equality in $\mathrm{C}_3$ with inequality, the optimization problem in (24) can be rewritten as

$$\begin{aligned}
\max_{\tilde{\mathcal{R}},\tilde{\boldsymbol{p}},\tilde{\boldsymbol{\theta}}} \quad & \tilde{\mathcal{R}} \\
\text{s.t.} \quad & \mathrm{C}_1: \ln\!\left(\frac{p_{I,j}\exp(-\tilde{p}_n)+\exp(-\tilde{p}_n-\tilde{\theta}_j)}{g_j} + \sum_{i=n+1}^{N}\exp(\tilde{p}_i-\tilde{p}_n)\right) \\
& \quad + \ln(2^{\frac{\alpha\exp(\tilde{\mathcal{R}})}{\tau}}-1) \leq 0,\ \forall n\in\mathcal{N}, j\in\{n,...,N\}, \\
& \mathrm{C}_2: \sum_{n\in\mathcal{M}_k}\exp(\tilde{\theta}_n)g_n(g_np+p_{I,n})+ \\
& \quad \tfrac{(1-\tau)(P_I+1)}{\eta\tau}2^{\frac{\beta|\mathcal{M}_k|\exp(\tilde{\mathcal{R}})}{1-\tau}} \leq \sum_{n\in\mathcal{M}_k}g_n(g_np+p_{I,n}) \\
& \quad + \tfrac{(1-\tau)(p_I+1)}{\eta\tau},\ \forall\mathcal{M}_k\subseteq\mathcal{N}, \\
& \mathrm{C}_3: \textstyle\sum_{n=1}^{N}\exp(\tilde{p}_n)\leq p, \\
& \mathrm{C}_4: \tilde{\theta}_n\leq 0,\ \forall n\in\mathcal{N}.
\end{aligned} \tag{25}$$

Note that the left inequality of $\mathrm{C}_4$ and $\mathrm{C}_5$ of the optimization problem in (24) are always valid, thus, they vanish from (25).

*Proposition 2:* The optimization problem in (25) is convex.

*Proof:* The objective function of (25) and $\mathrm{C}_4$ are linear. Regarding $\mathrm{C}_1$, the first term is a convex log-sum-exp function [57], while the second term, i.e.,

$$f=\ln(2^{\frac{\alpha\exp(\tilde{\mathcal{R}})}{\tau}}-1) \tag{26}$$

is also convex, considering that $\frac{\partial^2 f}{\partial\mathcal{R}^2}\geq 0$ [57]. This can be easily proved, since

$$\frac{\partial^2 f}{\partial\mathcal{R}^2}=\frac{2^z z\ln(2)\,(2^z-z\ln(2)-1)}{(2^z-1)^2}, \tag{27}$$

with $z=\frac{\alpha\exp(\tilde{\mathcal{R}})}{\tau}$. Note that $w=2^z-z\ln(2)-1$ is an increasing function with respect to $z$ and when $z\to 0$, $w\to 0$. Finally, the left side of the constraint $\mathrm{C}_3$ is a sum-exp function and, thus, convex. ■

Proposition 2 is also critical, since it proves that (25) can be optimally solved in polynomial time, by well-known algorithms, such as the interior-point method [57].

*1) Special Case: Interference-free Communication:* In this subsection, we focus on the absence of interference, and, thus, mainly on the parts of (21) that change. First, the constraint $\mathrm{C}_1$ can be replaced by two simpler constraints i.e. (7) and (8). Moreover, when interference is zero, the inequality in (20) can be rewritten as

$$\sum_{n\in\mathcal{M}_k}R_n^u\leq(1-\tau)\log_2\left(1+\frac{(\eta\tau\sum_{i=1}^{N}p_i^d)\sum_{n\in\mathcal{M}_k}(1-\theta_n)g_n^2}{1-\tau}\right),$$
$$\forall\mathcal{M}_k:\mathcal{M}_k\subseteq\mathcal{N}. \tag{28}$$

Consequently, using the epigraph form, the minimum rate maximization problem can be expressed as

$$\begin{aligned}
\max_{\mathcal{R},\tau,\boldsymbol{p},\boldsymbol{\theta}} \quad & \mathcal{R} \\
\text{s.t.} \quad & \mathrm{C}_{1a}: \theta_ng_n\leq\theta_{n+1}g_{n+1},\ \forall n\in\{1,...,N-1\}, \\
& \mathrm{C}_{1b}: \tau\log_2\left(1+\frac{p_n^d\theta_ng_n}{\theta_ng_n\sum_{i=n+1}^{N}p_i^d+1}\right)\geq\alpha\mathcal{R},\ \forall n\in\mathcal{N}, \\
& \mathrm{C}_2: (1-\tau)\log_2\left(1+\frac{(\eta\tau\sum_{i=1}^{N}p_i^d)\sum_{n\in\mathcal{M}_k}(1-\theta_n)g_n^2}{1-\tau}\right)\geq \\
& \quad \beta|\mathcal{M}_k|\mathcal{R},\ \forall\mathcal{M}_k\subseteq\mathcal{N}, \\
& \mathrm{C}_3: \textstyle\sum_{n=1}^{N}p_n^d\leq p, \\
& \mathrm{C}_4: 0\leq\theta_n\leq 1,\ \forall n\in\mathcal{N}, \\
& \mathrm{C}_5: p_n^d\geq 0,\ \forall n\in\mathcal{N}, \\
& \mathrm{C}_6: 0\leq\tau\leq 1,
\end{aligned} \tag{29}$$

Subsequently, using one-dimensional search for the optimization of $\tau$ and similar steps as the ones in the previous subsection, (29) can be rewritten as

$$\begin{aligned}
\max_{\tilde{\mathcal{R}},\tilde{\boldsymbol{p}},\tilde{\boldsymbol{\theta}}} \quad & \tilde{\mathcal{R}} \\
\text{s.t.} \quad & \mathrm{C}_{1a}: \tilde{\theta}_n-\tilde{\theta}_{n+1}\leq\ln\left(\frac{g_{n+1}}{g_n}\right),\ \forall n\in\{1,...,N-1\}, \\
& \mathrm{C}_{1b}: \ln\left(\frac{\exp(-\tilde{p}_n-\tilde{\theta}_n)}{g_n}+\sum_{i=n+1}^{N}\exp(\tilde{p}_i-\tilde{p}_n)\right) \\
& \quad + \ln(2^{\frac{\alpha\exp(\tilde{\mathcal{R}})}{\tau}}-1)\leq 0,\ \forall n\in\mathcal{N}, \\
& \mathrm{C}_2: \sum_{n\in\mathcal{M}_k}\exp(\tilde{\theta}_n)g_n^2+\tfrac{1-\tau}{\eta p\tau}2^{\frac{\beta|\mathcal{M}_k|\exp(\tilde{\mathcal{R}})}{1-\tau}} \\
& \quad \leq\sum_{n\in\mathcal{M}_k}g_n^2+\tfrac{1-\tau}{\eta p\tau},\ \forall\mathcal{M}_k\subseteq\mathcal{N}, \\
& \mathrm{C}_3: \textstyle\sum_{n=1}^{N}\exp(\tilde{p}_n)\leq p, \\
& \mathrm{C}_4: \tilde{\theta}_n\leq 0,\ \forall n\in\mathcal{N}.
\end{aligned} \tag{30}$$

Considering Proposition 2 and the linearity of $\mathrm{C}_{1a}$, it can be easily proved that the optimization problem in (30) is a convex one. Taking into account the replacement of $\mathrm{C}_1$ with $\mathrm{C}_{1a}$ and $\mathrm{C}_{1b}$, it is observed that (30) is simpler than (25) since the $\sum_{i=0}^{N-1}N-i$ nonlinear constraints are replaced by $N-1$ linear constraints and solely $N$ nonlinear ones.

## B. Downlink with TDMA

The minimum rate maximization problem Taking into acount (17) and (14), the constraint in (16) can be rewritten as

$$\sum_{n\in\mathcal{M}_k}R_n^u\leq(1-\tau)\times$$
$$\log_2\left(1+\frac{\eta\sum_{n\in\mathcal{M}_k}g_n\left((g_np+p_{I,n})\sum_{i\in\mathcal{N}}t_i-\theta_n(g_npt_n+p_{I,n})\right)}{(1-\tau)(1+p_I)}\right),$$
$$\forall\mathcal{M}_k:\mathcal{M}_k\subseteq\mathcal{N}. \tag{31}$$

The minimum rate maximization problem, using the epigraph form, as in (21), can be written as

$$\begin{aligned}\max_{\mathcal{R},\tau,\boldsymbol{t},\boldsymbol{\theta}} \quad & \mathcal{R}\\ \textbf{s.t.} \quad & \mathrm{C}_1: t_n\log_2\left(1+\tfrac{\theta_n p g_n}{\theta_n p_{I,n}+1}\right)\geq \alpha\mathcal{R},\,\forall n\in\mathcal{N},\\ & \mathrm{C}_2: (1-\tau)\times\\ & \log_2\left(1+\frac{\eta\sum\limits_{n\in\mathcal{M}_k} g_n\left((g_np+p_{I,n})\sum\limits_{i\in\mathcal{N}}t_i-\theta_n t_n(g_np+p_{I,n})\right)}{(1-\tau)(1+p_I)}\right)\\ & \quad\geq\beta|\mathcal{M}_k|\mathcal{R},\,\forall\mathcal{M}_k\subseteq\mathcal{N},\\ & \mathrm{C}_3: \textstyle\sum_{n=1}^N t_n\leq\tau,\\ & \mathrm{C}_4: 0\leq\theta_n\leq 1,\,\forall n\in\mathcal{N},\\ & \mathrm{C}_5: t_n\geq 0,\,\forall n\in\mathcal{N},\\ & \mathrm{C}_6: 0\leq\tau\leq 1,\end{aligned}\tag{32}$$

where $\mathrm{C}_1$, $\mathrm{C}_2$, and $\mathrm{C}_3$ correspond to (13) and (18), (19) and (31), and (10), respectively, while the rest of the constraints (i.e., $\mathrm{C}_4$-$\mathrm{C}_6$) limit the optimized variables not to exceed their maximum/minimum value.

*Proposition 3:* The inequality in $\mathrm{C}_3$ can be replaced by equality without excluding the optimal from the set of all solutions.

*Proof:* The proof is similar to that of Proposition 1. ■

Considering Proposition 3, $\mathrm{C}_2$ can be replaced by

$$\begin{aligned}&\sum_{n\in\mathcal{M}_k}R_n^u\leq(1-\tau)\times\\ &\log_2\left(1+\frac{\eta\sum\limits_{n\in\mathcal{M}_k}g_n\left((g_np+p_{I,n})\tau-\theta_n t_n(g_np+p_{I,n})\right)}{(1-\tau)(1+p_I)}\right),\\ &\forall\mathcal{M}_k:\mathcal{M}_k\subseteq\mathcal{N}.\end{aligned}\tag{33}$$

Moreover, one-dimensional search is assumed for the optimization of $\tau$. However, even with these simplifications, the optimization problem in (32), remains non-convex due to the coupling of the variables $\boldsymbol{\theta}$ and $\boldsymbol{t}$.

Next, by setting $t_n\triangleq\exp(\tilde{t}_n)$, $\theta_n\triangleq\exp(\tilde{\theta}_n)$, and $\mathcal{R}\triangleq\exp(\tilde{\mathcal{R}})$, the optimization problem in (32) can be rewritten as

$$\begin{aligned}\max_{\tilde{\mathcal{R}},\tilde{\boldsymbol{t}},\tilde{\boldsymbol{\theta}}} \quad & \tilde{\mathcal{R}}\\ \textbf{s.t.} \quad & \mathrm{C}_1: \exp(\tilde{t}_n)\log_2\left(1+\tfrac{\exp(\tilde{\theta}_n)pg_n}{\exp(\tilde{\theta}_n)p_{I,n}+1}\right)\\ & \quad\geq\alpha\exp(\tilde{\mathcal{R}}),\,\forall n\in\mathcal{N},\\ & \mathrm{C}_2: (1-\tau)\times\\ & \log_2\left(1+\frac{\eta\sum\limits_{n\in\mathcal{M}_k}g_n\left((g_np+p_{I,n})\tau-\exp(\tilde{\theta}_n+\tilde{t}_n)(g_np+p_{I,n})\right)}{(1-\tau)(1+p_I)}\right)\\ & \quad\geq\beta|\mathcal{M}_k|\exp(\tilde{\mathcal{R}}),\,\forall\mathcal{M}_k\subseteq\mathcal{N}\\ & \mathrm{C}_3: \textstyle\sum_{n=1}^N\exp(\tilde{t}_n)=\tau,\\ & \mathrm{C}_4: 0\leq\exp(\tilde{\theta}_n)\leq 1,\\ & \mathrm{C}_4: \exp(\tilde{t}_n)\geq 0,\end{aligned}\tag{34}$$

which, after some mathematic manipulations and by relaxing the equality in $\mathrm{C}_3$ with inequality, can be expressed as

$$\begin{aligned}\max_{\tilde{\mathcal{R}},\tilde{\boldsymbol{t}},\tilde{\boldsymbol{\theta}}} \quad & \tilde{\mathcal{R}}\\ \textbf{s.t.} \quad & \mathrm{C}_1: \ln\left(2^{\alpha\exp(\tilde{\mathcal{R}}-\tilde{t}_n)}-1\right)+\ln\left(p_{I,n}+\exp(-\tilde{\theta}_n)\right)\leq\\ & \ln(pg_n),\,\forall n\in\mathcal{N},\\ & \mathrm{C}_2: \sum_{n\in\mathcal{M}_k}\exp(\tilde{\theta}_n+\tilde{t}_n)g_n(g_np+p_{I,n})+\\ & \tfrac{(1-\tau)(1+p_I)}{\eta}2^{\frac{\beta|\mathcal{M}_k|\exp(\tilde{\mathcal{R}})}{1-\tau}}\leq\tau\sum_{n\in\mathcal{M}_k}g_n(g_np+p_{I,n})\\ & +\tfrac{(1-\tau)(1+p_I)}{\eta},\,\forall\mathcal{M}_k\subseteq\mathcal{N},\\ & \mathrm{C}_3: \textstyle\sum_{n=1}^N\exp(\tilde{t}_n)\leq\tau,\\ & \mathrm{C}_4: \tilde{\theta}_n\leq 0,\,\forall n\in\mathcal{N}.\end{aligned}\tag{35}$$

Note that the left inequality of $\mathrm{C}_4$ and $\mathrm{C}_5$ of the optimization problem in (34) are always valid, thus, they vanish from (35).

*Proposition 4:* The optimization problem in (35) is convex.

*Proof:* The proof is similar to that of Proposition 2. Note that the first term of the left side of $\mathrm{C}_1$, i.e.,

$$f=\ln\left(2^{\alpha\exp(\tilde{\mathcal{R}}-\tilde{t}_n)}-1\right)\tag{36}$$

is a function of the variables $\tilde{\mathcal{R}}$ and $\tilde{t}_n$, thus its convexity must be proved considering its Hessian matrix rather than its second derivatives. More specifically, its Hessian matrix has non-negative eigenvalue, which is

$$\phi=\frac{2^{z+1}z\ln(2)\left(2^z-z\ln(2)-1\right)}{(2^z-1)^2},\tag{37}$$

where $z=\alpha\exp(\tilde{\mathcal{R}}-\tilde{t}_n)$. ■

It needs to be mentioned that the optimization problem in (35) is simpler than (25), since it has a lower number of non-linear constraints due to $\mathrm{C}_1$.

## IV. Simulations and Discussions

In this section, simulation results are presented for a system with $N=2$ or $N=3$ users, for $\eta=0.5$. When $N=2$, the distances of the users from the BS are $d_1=5$ m and $d_2=1$ m, while for $N=3$, it is $d_1=5$ m, $d_2=3$ m, and $d_3=1$ m, respectively. We adopt a bounded path loss model

$$g_n=\frac{1}{1+d_n^{\xi}},\tag{38}$$

as in [27], where $\xi$ is the path-loss exponent, with $\xi=2$, while fast fading is neglected, in order to focus on the asymmetry of the system due to different user distances from the BS. The indexing of the users is in ascending order with respect to their channel gains, $g_n$. Finally, one-dimensional search is performed for the optimization of $\tau$, with a step of 0.01.

Regarding the source of interference, for the sake of convenience for the illustration, we consider a sole interfering source (IS), the distance of which from the BS is denoted by $D$. We consider that the BS, the users and the IS are located on a single line, connecting the BS and the IS. Then, the received interference by each user (normalized by the noise power) is given by

$$p_{I,n}=\frac{p_{IS}}{(1+(D-d_n)^{\xi})}\tag{39}$$

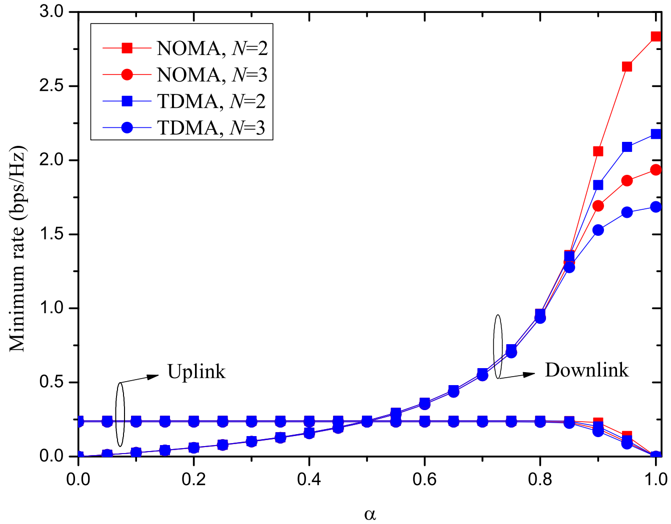


Fig. 2. Impact of $\alpha$ on the minimum rate, for $p = 40$ dB, $p_{IS} = 40$ dB, and $D = 20$ m.

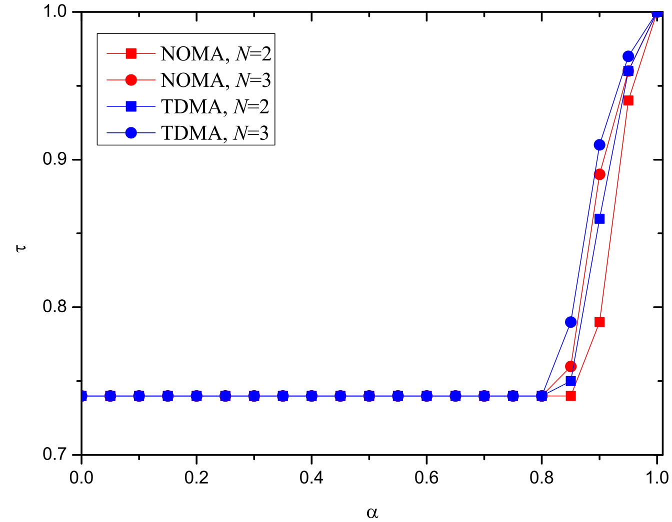


Fig. 3. Impact of $\alpha$ on $\tau$, for $p = 40$ dB, $p_{IS} = 40$ dB, and $D = 20$ m.

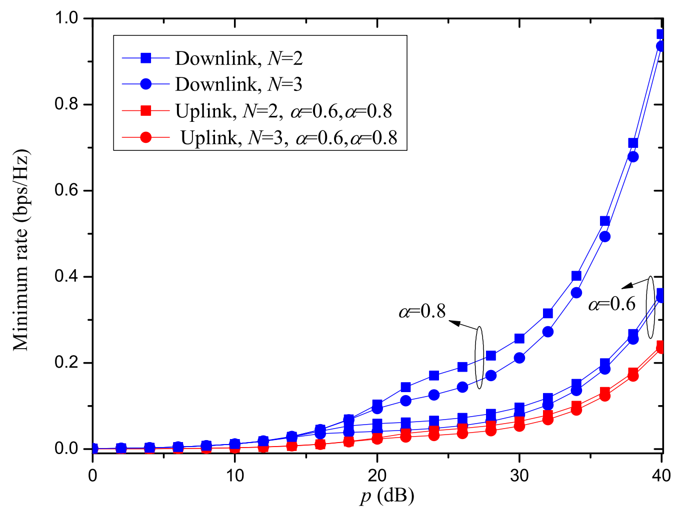


Fig. 4. Impact of $p$ on the minimum rate for $p_{IS} = 40$ dB, $D = 20$ m, and different values of $\alpha$.

where $p_{IS} = \frac{P_{IS}}{N_0}$, with $P_{IS}$ being the transmit power of the IS. Also, the normalized interference received by the BS is calculated as

$$p_I = \frac{p_{IS}}{(1 + D^{\xi})}. \tag{40}$$

Hereinafter, we assume that $p_{IS} = 40$ dB.

In Fig. 2, the rate achieved in the uplink and in the downlink, for $N = 2, 3$, is depicted with respect to the value of $\alpha$, in the presence of the IS. It is obvious that in the case of $\alpha < 0.5$, the uplink rate cannot be substantially increased, by either of the two protocols used during the downlink, mainly because of the power that can be harvested and then reused during uplink. However, when priority is given to the downlink rate, i.e., for $\alpha > 0.5$, the downlink rate is substantially improved. Furthermore, for values $\alpha > 0.85$, the use of NOMA during downlink offers a considerable gain in the achieved rate, for both values of the number of users, compared to TDMA. Therefore, it is concluded that the NOMA protocol in the downlink can provide more fair performance to the users than TDMA, even in the presence of interference.

In Fig. 3, the optimized $\tau$ that is dedicated to the downlink is depicted with respect to the value of $\alpha$, for the same setup as in Fig. 2. It is easily observed that, for $\alpha < 0.8$, the time allocated for the downlink is practically unaltered. Thus, comparing to Fig. 2, one can conclude that the achieved minimum uplink rates and the optimal time allocation do not change considerably for $\alpha < 0.8$, while the increase in the value of the minimum downlink rates is mainly due to the different power allocation and power splitting, and not due to a different optimal value for the time allocation factor $\tau$. However, for $\alpha > 0.8$, when priority is given mainly to the downlink, the time allocated for downlink (and thus for energy harvesting as well) substantially increases, which leads to a considerable increase in the downlink rates. It is further observed by Fig. 3 that the time allocated for downlink is higher in the case of TDMA, rather than for NOMA. This indicates that more harvested energy is needed for TDMA. Taking into account that NOMA achieves better rates with less harvested power, it is induced that NOMA is more energy efficient than TDMA for the downlink.

In Fig. 4, we investigate the achieved minimum rate in the uplink and the downlink, when $\alpha = 0.6$ and $\alpha = 0.8$, with respect to the total transmit power of the BS, $p$. The IS is located again at distance $D = 20$ m, with transmit power $p_{IS} = 40$ dB. From Fig. 2, one can observe that, when $p = 40$ dB, the uplink rate is practically the same, for both values of $\alpha$. Furthermore, both NOMA and TDMA achieve the same uplink rate for these values of $\alpha$. This is observed for other values of $p$ as well, thus the uplink rate is plotted only once in Fig. 4 for each number of users. However, the downlink rate, although it is practically the same for both protocols, it differs according to the choice of $\alpha$, since $\alpha = 0.8$ leads to higher rate, i.e., when priority is given to the downlink. For both values of $\alpha$, it is easily seen that, for transmit power $p > 30$ dB, the rate increases faster, compared to transmit

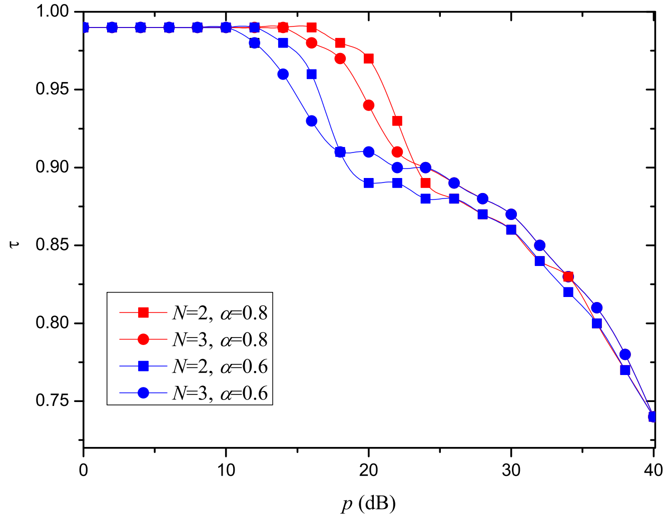


Fig. 5. Impact of $p$ on $\tau$ for $p_{IS} = 40$ dB, $D = 20$ m, and different values of $\alpha$.

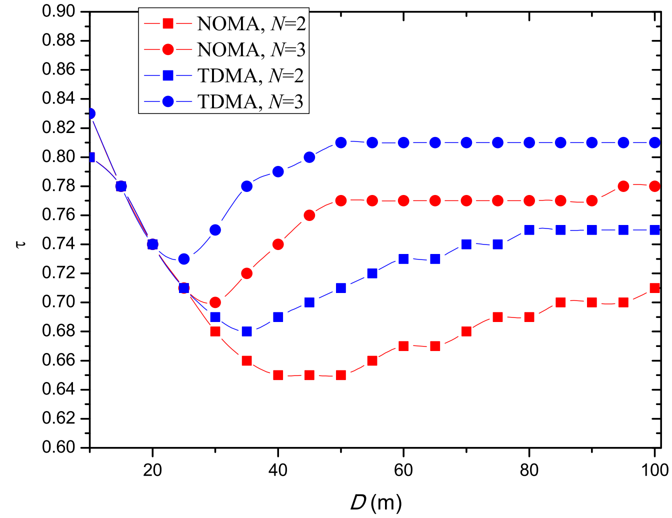


Fig. 7. Impact of $D$ on $\tau$, for $p = 40$ dB, $p_{IS} = 40$ dB, $\alpha = 0.8$.

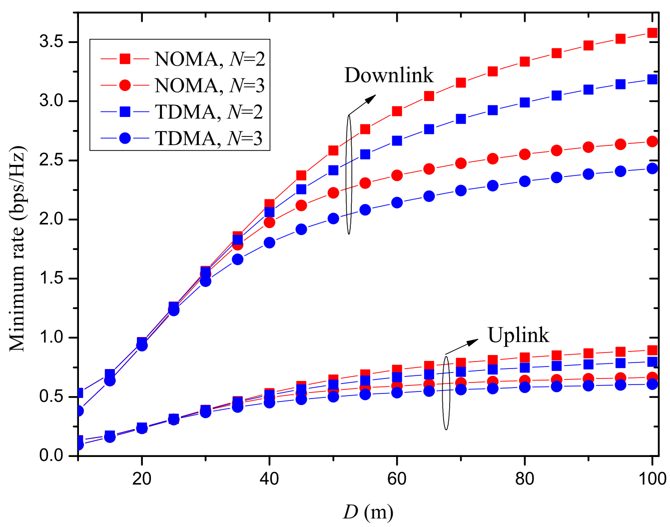


Fig. 6. Impact of $D$ on the minimum rate, for $p = 40$ dB, $p_{IS} = 40$ dB, $\alpha = 0.8$.

power values between 20 and 30 dB. This indicates that, when $p = 30$ dB, the interference imposed by the IS can now be mitigated easier, due to the available transmit power at the BS, achieving increasing data rates. This is more obvious for higher values of $\alpha$.

Accordingly, in Fig. 5, the impact of $p$ on the allocated time $\tau$ to the downlink, is illustrated for $\alpha = 0.6$ and $\alpha = 0.8$. Again, the results of both NOMA and TDMA are the same, so they are plotted only once. It is easily seen that, for both numbers of users, $N = 2, 3$, when $\alpha = 0.8$, more time is allocated to the downlink and, consequently, to the energy harvesting, which is expected, since the downlink is given higher priority.

In Figs. 6 and 7, we consider a system with $N = 2, 3$ users as in the previous cases, but we examine the impact of the distance $D$, at which the IS is located, on the achieved uplink/downlink rate and the optimized allocated time $\tau$, for both NOMA and TDMA protocols. More specifically, the distance $D$ varies between $D = 10$ and $D = 100$ m. From Fig. 6, it is easily observed that, when the IS is located further from the users and the BS, i.e. when the power of the interference is low, NOMA achieves substantial gains, both for the uplink and the downlink rates, compared to TDMA. This is mostly evident for $D > 40$ m. Therefore, NOMA seems to be less prone to interference than TDMA, when the received unwanted power is low. Furthermore, from Fig. 7, the TDMA protocol requires more time $\tau$ allocated to the downlink and therefore, to energy harvesting, especially when the IS is located further from the BS and the users. This indicates that the NOMA protocol is more energy efficient from TDMA, since it achieves better performance, with less harvested energy, for varying power levels of interference.

Motivated by the energy efficiency and the resilience towards low levels of interference that NOMA presents compared to TDMA, we next present numerical results for the case of interference-free communication, in order to investigate the performance gains offered by NOMA in the downlink, compared to TDMA, in absence of interfering sources.

### A. *Interference-free Communication*

In this subsection, we present numerical results for the special case when no interference is considered. More specifically, in Fig. 8, the rate achieved in the uplink and in the downlink, for $N = 2, 3$, is depicted with respect to the value of $\alpha$. As expected, when $\alpha > 0.5$, since the downlink is prioritized over the uplink, the achieved rate for the downlink is higher. However, in the absence of interference, the impact of the value of $\alpha$ is more evident on the achieved rates, since for $\alpha > 0.5$, the uplink rate decreases, while the downlink rate is substantially increased. Regarding the comparison between NOMA and TDMA for the downlink, the two protocols seem to perform similarly, when priority is given for the uplink rate, i.e., when $\alpha < 0.5$. However, for $\alpha > 0.5$, NOMA outperforms TDMA in the end-to-end optimization, achieving higher rates for the uplink and downlink, when compared to TDMA, in contrast to the case of interference, when NOMA

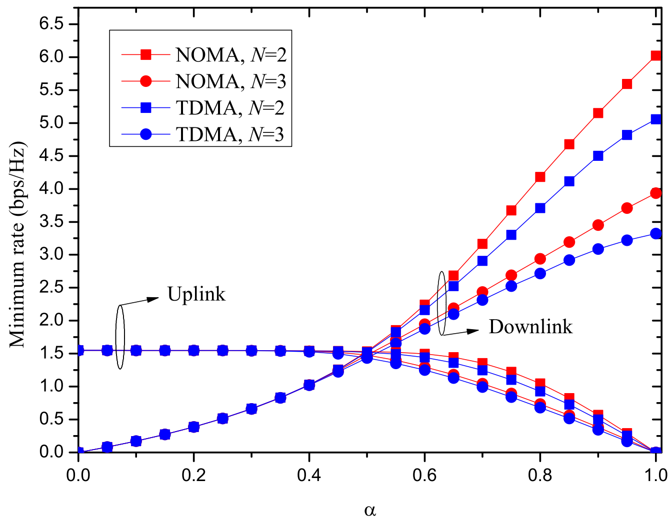


Fig. 8. Impact of $\alpha$ on the minimum rate, for $p = 40$ dB.

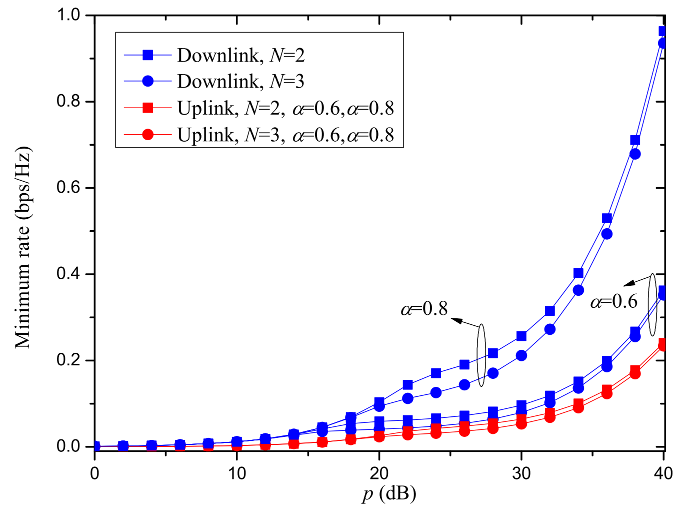


Fig. 10. Impact of $p$ on the minimum rate, for $\alpha = 0.8$.

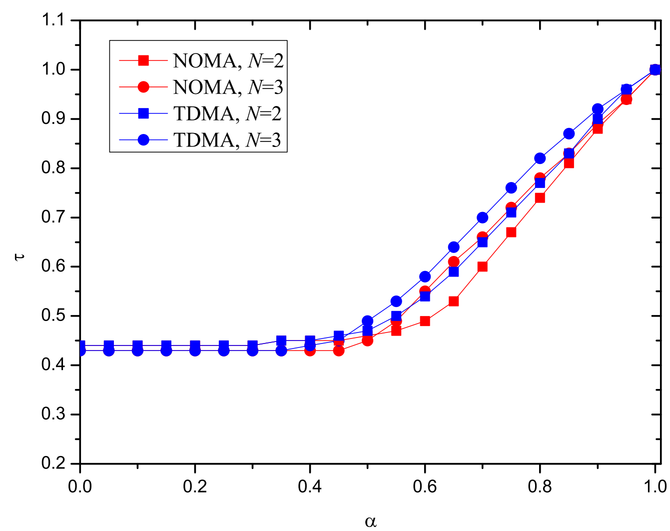


Fig. 9. Impact of $\alpha$ on $\tau$, for $p = 40$ dB.

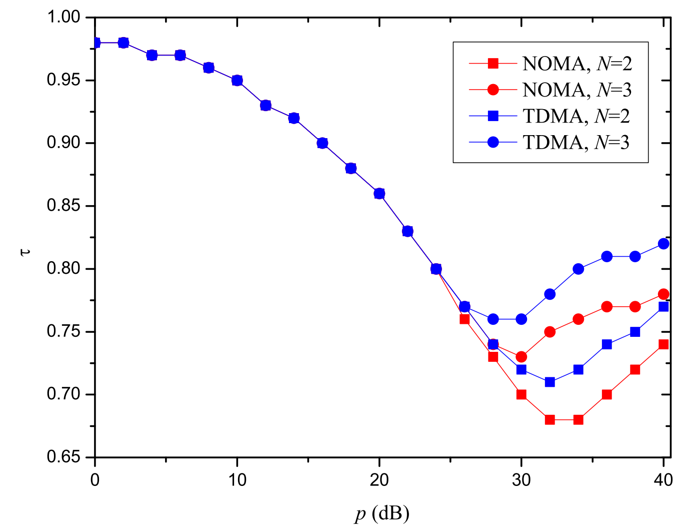


Fig. 11. Impact of $p$ on $\tau$, for $\alpha = 0.8$.

outperformed TDMA only for values of $\alpha > 0.8$. In Fig. 8, it can be seen that NOMA can achieve the same downlink rate with TDMA but for a lower value of $\alpha$, which translates in higher uplink rate. For example, the highest downlink rate achieved by TDMA, which is for $\alpha = 1$ when the uplink rate is zero, is achieved by NOMA for $\alpha \approx 0.85$, where the uplink rate is non-zero. When $N$ increases, the achieved rate is reduced, however it also depends on the choice of $\alpha$, thus revealing a tradeoff between the desired rate and the prioritization between the downlink and the uplink.

In Fig. 9, the same setup as Fig. 8 is examined, but the optimized time fraction dedicated to the downlink phase when the users harvest energy is depicted with respect to the value of $\alpha$, for both protocols used in the downlink. Comparing with Fig. 3 where interference is present, we observe that the time allocated for the downlink increases for values of $\alpha > 0.5$, instead of $\alpha > 0.8$. In the case of interference-free communication, similarly to Fig. 3, TDMA requires more time dedicated to the downlink and thus for energy harvesting, indicating once more that NOMA is a more energy-efficient solution than TDMA.

In Fig. 10, the achieved rate for the downlink and the uplink is presented, with respect to the transmit signal-to-noise ratio, $p$, when $\alpha = 0.8$. One can observe that NOMA performs better than TDMA, as $p$ increases, in contrast to the case of interference, when both protocols achieved the same performance, for $\alpha = 0.8$. Another useful observation from this figure, but also from Fig. 4, is the fact that, for $N = 3$, the rate increases with a smaller slope as $p$ increases, which is expected since it reflects the congestion of the multiple access schemes in use, as the number of users increases.

In Fig. 11, the optimal value of $\tau$ is plotted against the value of $p$, when $\alpha = 0.8$, in the absence of interference. A very interesting observation is that, although the time dedicated to the downlink - and, consequently, to the energy harvesting - decreases as $p$ increases, this is reversed after a value for $p$, for both $N = 2$ and $N = 3$, implying that higher availability

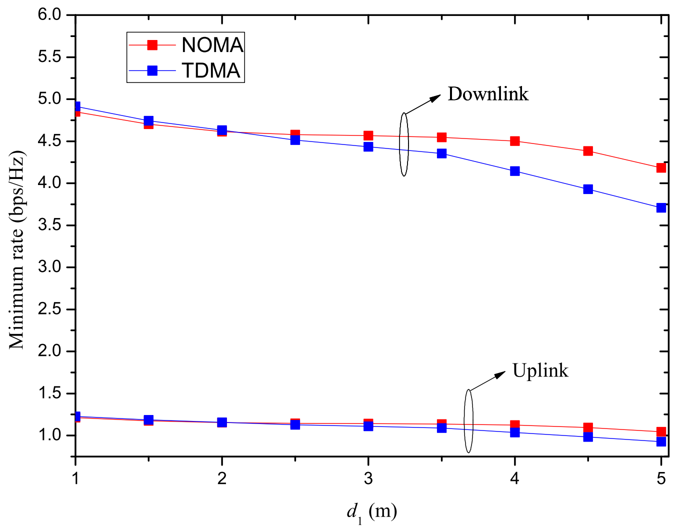


Fig. 12. The impact of distance on the minimum rate, for $\alpha = 0.8$, $p = 40$ dB, and $d_2 = 1$ m.

of power at the BS will require more time dedicated to the downlink, after that value of $p$. This can be explained as follows: as observed in Fig. 10 for $N = 3$, the slope of the rate increase is smaller for large $p$. Thus, increasing only the available power at the BS leads to saturation regarding the achievable rate, and therefore, further optimization can be achieved mainly by increasing the time dedicated to downlink, and not the transmit power.

Finally, in Fig. 12, where only two users are assumed in the absence of interfering source, the impact of asymmetric distances between the users and the BS is investigated. More specifically, the achieved rate is illustrated with respect to the distance of the first user, when the distance of the second user is fixed to $d_2 = 1$ m, while $\alpha = 0.8$ and $p = 40$ dB. The gains in terms of achieved rate that NOMA can offer compared to TDMA in the downlink are greater, as the CnfP becomes more intense. Thus, it is clear that the NOMA scheme can offer more fairness than TDMA, when users are asymmetrically located with respect to the BS.

## V. Conclusions and Future Directions

In this paper, both the downlink and the uplink of a wireless powered network, in the presence of interference, were optimized. Two different protocols were utilized for the downlink, i.e., NOMA and TDMA, while NOMA with time sharing was used for the uplink. The formulated optimization problems maximize the minimum rate among users, which is achieved both in the downlink and the uplink, by introducing corresponding priority weights. Furthermore, all the parameters regarding the energy harvesting of the users were optimized during the downlink, both for NOMA and TDMA.

For this reason, we studied the structure of the formulated non-convex multidimensional optimization problems and successfully transformed them into the equivalent convex ones, which can be solved with polynomial complexity. The results revealed an interesting dependence among the harvested energy, the achieved minimum downlink/uplink rate, the interference which is imposed on the communication network, and energy efficiency achieved by the implemented protocols. More specifically, the results showed that:

- A relatively high downlink rate can be achieved, while the required energy is simultaneously harvested by the users for the uplink, even at the presence of interference.
- When NOMA is utilized in the downlink, it can offer substantial gains, compared to TDMA, especially in the cases when the downlink is prioritized, and when the users are asymmetrically positioned, i.e., when the cascaded near-far problem appears. This gain offered by the NOMA protocol is especially achieved when the interference power level is low, or in the absence of interference.
- The performance of the network, when NOMA is utilized, is achieved requiring less energy transmission by the BS, revealing the energy efficiency of the NOMA protocol, compared to TDMA, when applied to wireless powered networks.

The analysis presented in this paper can be extended to several directions. First, apart from its combination with decoding techniques such as SIC and time-sharing, further improvement in performance is expected when more complex configuration at the BS is assumed, such as multiple antennas, beamforming, and scheduling. Second, it is interesting to extend our design to address the case of users with energy storage units. Of course, this will introduce optimization problems, where the challenge will be to solve them with acceptable complexity. Finally, our system model can be extended to a scenario of heterogeneous users that need access to different applications, and, thus, they do not acquire the same quality of service, where different priority must be given to each user.

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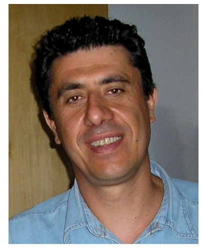

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